

# Analysis of AGS E880 Polarimeter at $G_{\gamma} = 12.5$

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High Energy Physics Division

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## Abstract

Data were collected with the AGS internal (E880) polarimeter at  $G\gamma = 12.5$  during the FY04 polarized proton run. Measurements were made with forward scintillation counters in coincidence with recoil counter telescopes, permitting an absolute calibration of the polarimeter for both nylon and carbon targets. The results are summarized and they will also be useful for an absolute calibration of the AGS CNI polarimeter at  $G\gamma = 12.5$ .

## I. INTRODUCTION

For many years, studies with polarized proton beams in the AGS have been performed to improve both the polarization and intensity. The E880 polarimeter has been used to provide measurements of the relative beam polarization over the full range of energies from injection to extraction. At a few energies, an absolute calibration of the E880 polarimeter has been performed, most recently at  $G\gamma = 7.5$  ( $p = 3.81$  GeV/c - see Ref. [1]). Earlier calibrations occurred at  $G\gamma = 10.5$  and  $14.5$  (Ref. [2]), and at  $41.5$  ( $21.7$  GeV/c, Ref. [3]). All calibrations were performed with detection of both the forward and recoil protons in coincidence except for Ref. [2]. One of the goals of this note is to provide another calibration point.

A Coulomb-nuclear interference (CNI) polarimeter using  $p + C$  elastic scattering was installed in the AGS ring before the FY03 run. The calibration of this instrument has been obtained from the E880 polarimeter at lower energies. A considerable change in the  $p + C$  analyzing power has been observed in the CNI region as a function of scattering angle and beam energy. A secondary goal of the present measurement is to provide an absolute calibration for the CNI polarimeter at  $G\gamma = 12.5$ .

This note closely follows the analysis described in Ref. [1] for data at  $G\gamma = 7.5$ . Small forward scintillation counters located immediately outside the AGS beam pipe were installed before the FY02 polarized run; see Fig. 1. For the calibration, signals from each counter were used in coincidence with those from the triple of recoil scintillation counters on the opposite side of the beam pipe (Ref. [3]). The locations and angles of the counters with respect to the beam were matched to  $pp$  elastic scattering kinematics near  $G\gamma = 12.5$  ( $p = 6.47$  GeV/c).

An attempt to calibrate the E880 polarimeter at  $G\gamma = 12.5$  was made during the FY03 polarized proton run. Unfortunately, the target insertion mechanism did not permit the nylon (fishline) target to be placed at the center of the beam pipe. Measurements with the beam offset by about  $1.7 - 2.0$  cm, near the maximum the nylon target could be inserted, were attempted. However, the results were internally inconsistent, with different sets of runs disagreeing. The target problem was fixed before the FY04 run.

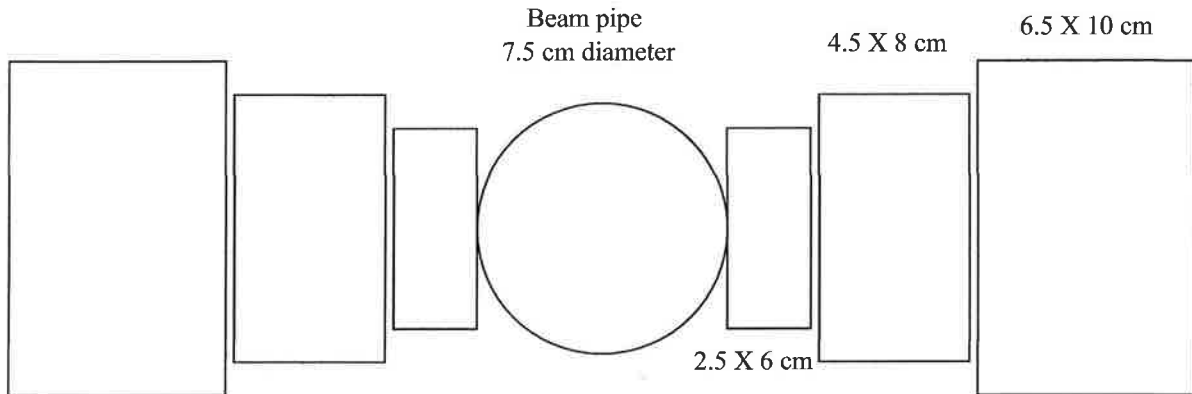


FIG. 1: *Sketch of the forward arms. The scintillation counters closest to the beam are for  $G\gamma = 12.5$  and the ones farthest from the beam pipe are for  $G\gamma = 4.7$ . The middle pair of counters were used for the  $G\gamma = 7.5$  calibration.*

## II. MEASUREMENTS

The calibration runs occurred on 28 April 2004 in the morning and early afternoon, during a RHIC access period. The beam intensity was adjusted to  $\sim 5 \times 10^9$  protons per AGS bunch to prevent destruction of the fishline target. The accelerator rf was turned off on flattop. One nylon and two carbon targets were mounted on the E880 target ladder, as at  $G\gamma = 7.5$  in Ref. [1]. The gating time for data collection was adjusted to begin after the rf was turned off and the target was inserted, and to end before the nominal end of flattop. The scintillation counter signals were viewed with an oscilloscope to insure there was no evidence for a drop in magnitude within the flattop (sagging) due to rate effects. All runs were made with the wedge degrader positions in each recoil telescope set to the nominal values for  $G\gamma = 12.5$ .

The E880 polarimeter high voltages and timings for recoil scintillation counters  $L_1$ ,  $L_2$ ,  $E_L$ ,  $R_1$ , and  $R_2$  remained unchanged for the  $G\gamma = 12.5$  measurements compared to the past several years operation. However, the high voltage for  $E_R$  was raised from 900 V to 925 or 950 V and the timing delay of this signal into the triple coincidence,  $ROLD = R_1 \cdot R_2 \cdot E_R$  was reduced by 2 nsec. These changes were made to balance the signal sizes in  $E_L$  and  $E_R$  and the coincidence rates for the two recoil telescopes. The target scan and data runs 5927 – 5932 occurred at 950 V, while runs 5933 – 5938 had 925 V. This difference will be shown to cause a negligible change in the resulting asymmetries and analyzing powers.

Figure 2 shows the results of a target scan taken immediately before the measurements. In this figure, the electronic OR of coincidences in the first two scintillation counters in each recoil telescope (i.e.,  $(L_1 \cdot L_2) \oplus (R_1 \cdot R_2)$  - see Ref. [3]) is plotted as a function of target position. Each point corresponds to the sum of five beam bunches. The data were taken first by incrementing the target position by 100 counts for successive points, and then additional values were measured for decreasing position. The adopted positions for the fishline and carbon runs were 2900 and 1650, respectively, near the peak count rates. Thus, carbon asymmetries were measured with the carbon target that was farther from the nylon target, to avoid possible background events.

The number and linear densities of the targets can be used to calculate the relative heights of the carbon and fishline peaks in Fig. 2. Viewing the carbon target with a microscope, it was estimated that 14-15 carbon fibers of diameter  $\sim 5.5 \mu m$  (nominally  $5.0 \mu m$ ) were used for these measurements, corresponding to a total linear density of  $7.9 - 8.4 \mu g/cm$ . The fishline was similar to that used in Ref. [1], and it had a linear density of  $107.6 \mu g/cm$ . Thus the ratio of fishline to carbon peak heights would be expected to be  $12.8 - 13.6$ , whereas a value closer to 5 is observed in Fig. 2. However, the significant loss of beam during the spill with the fishline target must also be taken into account. Unfortunately, detailed observations of this loss were not recorded during the measurements. A loss of a factor of  $2 - 4$  was estimated in Ref. [1] for  $G\gamma = 7.5$ , but the loss is expected to be somewhat less at the higher energy of these measurements due to reduced multiple scattering effects. Thus the observed ratio of 5 in peak heights in Fig. 2 may be (marginally) consistent with the calculated value  $\sim 13$ .

### III. ANALYSIS

The analysis will follow that in Ref. [1]. Defining the number of events from the nylon (fishline), carbon, hydrogen, and background (non-hydrogen in nylon) to be  $N_F$ ,  $N_C$ ,  $N_H$ , and  $N_B$ , respectively, then the number of forward-recoil coincidences can be written as:

$$\begin{aligned}
 (N_F)_{FR} &= [(1 - p) d\sigma_C + p d\sigma_H] \cdot I_F \\
 (N_C)_{FR} &= d\sigma_C \cdot I_C \\
 (N_B)_{FR} &= (1 - p) d\sigma_C \cdot I_F = (N_F)_{FR} - (N_H)_{FR}
 \end{aligned}
 \tag{1}$$

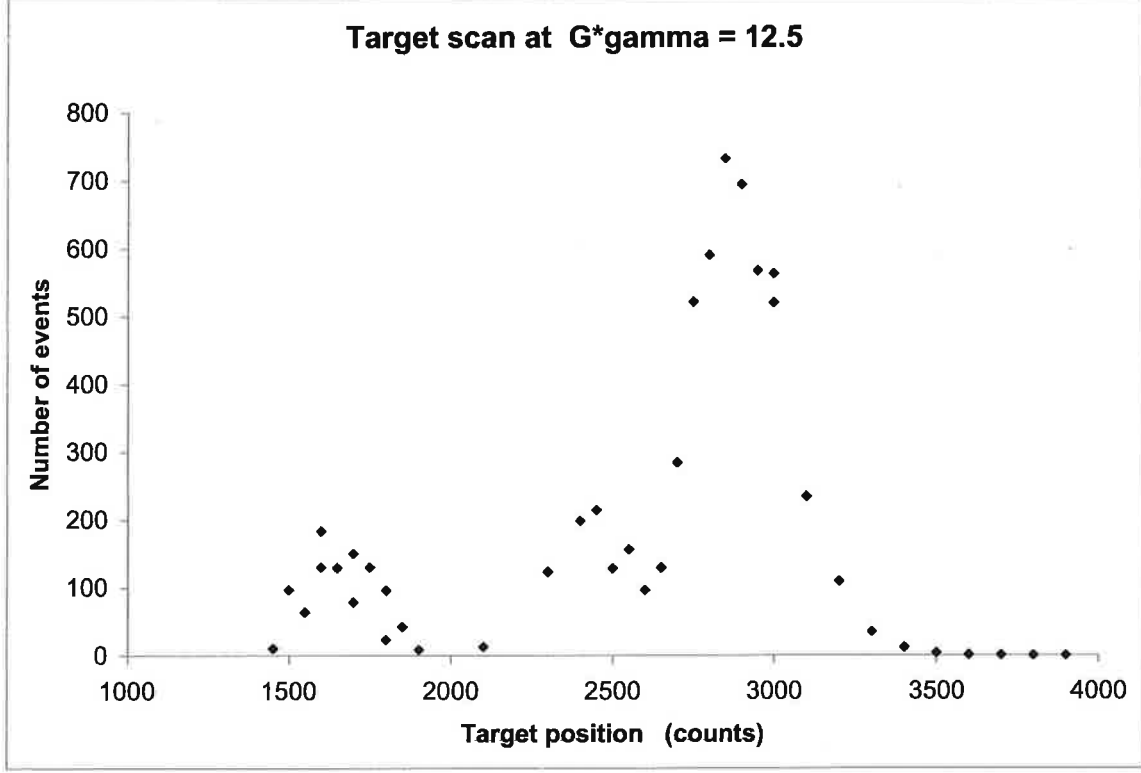


FIG. 2: *Target scan at  $G\gamma = 12.5$ . The horizontal axis is the target position measured in control counts, where 1000 counts is about 2.5 cm. The vertical axis is the relative number of events in the first two counters of the recoil telescopes.*

$$(N_H)_{FR} = p d\sigma_H \cdot I_F.$$

In these expressions,  $I_F$  and  $I_C$  are integrals of the beam current on the nylon and carbon targets, taking into account the beam spot shape, target linear density, beam lifetime, etc. The effective cross sections per nucleon for forward-recoil coincidences, weighted by acceptance of the detectors, are  $d\sigma_H$  and  $d\sigma_C$ . The percentage by weight of hydrogen in the nylon target is  $p \simeq 0.097$ , and the background fraction is

$$r = (N_B)_{FR} / (N_F)_{FR}.$$

The similar expressions for recoil counts only are

$$\begin{aligned} (N_F)_R &= [(1-p) A d\sigma_C + p B d\sigma_H] \cdot I_F \\ (N_C)_R &= A d\sigma_C \cdot I_C \end{aligned} \tag{2}$$

$$(N_B)_R = (1 - p) A d\sigma_C \cdot I_F = (N_F)_R - (N_H)_R$$

$$(N_H)_R = p B d\sigma_H \cdot I_F.$$

In Ref. [1] it is shown that

$$R = \frac{(N_C)_{FR}/(N_C)_R}{(N_F)_{FR}/(N_F)_R} \quad (3)$$

$$\simeq r \cdot (1.10 \pm 0.05),$$

thus permitting a good estimate of the background fraction. The summed left and right counts from the data runs were used to compute the value of  $R$ , as shown in Table I. Increasing the uncertainty on the value for the first set to compensate for the observed variation (see Table I caption) leads to

$$R = 0.1354 \pm 0.0046 \quad (\text{runs } 5927 - 5932)$$

$$= 0.1330 \pm 0.0011 \quad (\text{runs } 5933 - 5938)$$

and therefore

$$r = 0.1231 \pm 0.0070 \quad (\text{runs } 5927 - 5932)$$

$$= 0.1209 \pm 0.0056 \quad (\text{runs } 5933 - 5938), \quad (4)$$

where the uncertainty in the ratio between  $R$  and  $r$  from Eq. 3 has been taken into account. Note the ratios  $R$  and  $r$  are roughly 10% less than at  $G\gamma = 7.5$ .

The raw asymmetries measured for the carbon target runs are given in Table II and for the fishline target in Table III. All asymmetries were computed with the “square root formula”

$$\epsilon = \frac{\sqrt{L_{\uparrow}R_{\downarrow}} - \sqrt{L_{\downarrow}R_{\uparrow}}}{\sqrt{L_{\uparrow}R_{\downarrow}} + \sqrt{L_{\downarrow}R_{\uparrow}}}$$

for beam spin up and down ( $\uparrow, \downarrow$ ) and forward detectors to the left or right ( $L, R$ ) of the beam line. Typically, fishline runs were alternated with one or two carbon runs, as can be seen from the run numbers. All runs were  $\sim 8$  min in duration.

The two sets of runs, corresponding to different high voltages for  $E_R$ , will be treated separately for some of the initial calculations to demonstrate consistency. Weighted averages

Fishline runs	Carbon runs	R
5927	5928	$0.1390 \pm 0.0017$
5929	5930	$0.1412 \pm 0.0015$
5931	5932	$0.1268 \pm 0.0015$
5933	5934, 5935	$0.1334 \pm 0.0015$
5936	5937, 5938	$0.1325 \pm 0.0015$

TABLE I: *Values of the ratio of counts,  $R$ . The average for the first and second data sets are  $(0.1354 \pm 0.0009)$  and  $(0.1330 \pm 0.0011)$ , respectively. The chi-squared per degree of freedom for the first set is 26.2, while the second set results are statistically consistent.*

of the asymmetries are given in Tables II and III, yielding

$$\begin{aligned}
(\epsilon_F)_R/(\epsilon_C)_R &= 2.183 \pm 0.099 && (\text{runs } 5927 - 5932) \\
&= 2.425 \pm 0.143 && (\text{runs } 5933 - 5938) \\
&= 2.26 \pm 0.08 && (\text{wt.av.}),
\end{aligned}$$

and

$$\begin{aligned}
(\epsilon_F)_{FR}/(\epsilon_C)_{FR} &= 2.42 \pm 0.60 && (\text{runs } 5927 - 5932) \\
&= 1.58 \pm 0.33 && (\text{runs } 5933 - 5938) \\
&= 1.78 \pm 0.29 && (\text{wt.av.}).
\end{aligned}$$

These asymmetry ratios are consistent with those found at  $G\gamma = 7.5$  ( $2.342 \pm 0.043$  and  $1.791 \pm 0.059$ , respectively).

The asymmetries from the fishline can be expressed in terms of the asymmetries of its constituents

$$\epsilon_F = \epsilon_C \times r + \epsilon_H \times (1 - r)$$

Run number	Target position	Recoil asymmetry ( $\times 10^{-3}$ )	Forward*Recoil asymmetry ( $\times 10^{-3}$ )
5928	1650	$23.3 \pm 1.71$	$19.6 \pm 12.9$
5930	1650	$21.4 \pm 1.54$	$33.8 \pm 11.3$
5932	1650	$18.3 \pm 1.61$	$28.7 \pm 12.4$
5934	1650	$21.1 \pm 2.18$	$48.6 \pm 17.4$
5935	1650	$17.7 \pm 2.20$	$47.0 \pm 17.6$
5937	1650	$17.4 \pm 2.19$	$34.2 \pm 18.1$
5938	1650	$21.4 \pm 2.40$	$43.6 \pm 19.3$

TABLE II: *Magnitudes of asymmetries observed with the carbon target. The average recoil asymmetries for the first and second data sets are  $(20.92 \pm 0.93) \times 10^{-3}$  and  $(19.32 \pm 1.12) \times 10^{-3}$ , respectively. The corresponding asymmetries for recoil and forward coincidences are  $(28.0 \pm 7.0) \times 10^{-3}$  and  $(43.5 \pm 9.0) \times 10^{-3}$ .*

which gives

$$\begin{aligned}
\epsilon_H &= (73.32 \pm 1.51 \pm 0.92) \times 10^{-3} && (\text{runs } 5927 - 5932) \\
&= (72.37 \pm 1.96 \pm 0.84) \times 10^{-3} && (\text{runs } 5933 - 5938) \\
&= (72.97 \pm 1.20 \pm 0.90) \times 10^{-3} && (\text{wt.av.}),
\end{aligned} \tag{5}$$

where the first uncertainty corresponds to the errors on  $\epsilon_C$  and  $\epsilon_F$ , and the second is from the uncertainty on  $r$  from Eq. 4. The results from the two sets of runs are seen to be consistent.

#### IV. RESULTS

The  $pp$  elastic analyzing power ( $A_{pp}$ ) has been derived using both a fit to the world's data some time ago (Ref. [4]) and directly from nearby measurements. For  $pp$  elastic scattering,

Run number	Target position	Recoil asymmetry ( $\times 10^{-3}$ )	Forward*Recoil asymmetry ( $\times 10^{-3}$ )
5927	2900	$45.8 \pm 0.66$	$69.6 \pm 1.79$
5929	2900	$45.2 \pm 0.65$	$64.9 \pm 1.75$
5931	2900	$46.0 \pm 0.63$	$68.7 \pm 1.66$
5933	2900	$47.4 \pm 0.71$	$67.0 \pm 1.88$
5936	2900	$46.3 \pm 0.71$	$70.8 \pm 1.90$

TABLE III: *Magnitudes of asymmetries observed with the nylon target. The average recoil asymmetries for the first and second data sets are  $(45.67 \pm 0.37) \times 10^{-3}$  and  $(46.85 \pm 0.50) \times 10^{-3}$ , respectively. The corresponding asymmetries for forward and recoil coincidences are  $(67.74 \pm 1.00) \times 10^{-3}$  and  $(68.88 \pm 1.34) \times 10^{-3}$ .*

the 4-momentum transfer squared is given by

$$-t = 4M^2 \left( \frac{\frac{E_{in}-M}{E_{in}+M} \cos^2 \theta_R}{1 - \frac{E_{in}-M}{E_{in}+M} \cos^2 \theta_R} \right),$$

where the incident total energy is  $E_{in}$ , the proton mass is  $M$ , and the laboratory recoil angle is  $\theta_R$ . There are two estimates of the recoil angles because of an uncertainty in the target position along the beam direction,  $77.25^\circ$  and  $78.2^\circ$ . For 6.47 GeV/c, this corresponds to  $-t = 0.133$  or  $0.114$  GeV<sup>2</sup>/c<sup>2</sup>, respectively. The global fit gives  $A_{pp} = 0.1213$  and  $0.1171$  at these angles. The fit relies heavily on CERN and ZGS data near 6.0 GeV/c (Refs. [5–8]).

An alternate approach is to estimate  $A_{pp}$  directly from the 6.00 GeV/c measurements and extrapolate to 6.47 GeV/c ( $G\gamma = 12.5$ ). The data from Refs. [5–8] are plotted with statistical uncertainties in Fig. 3. The mean value from all data in the interval  $-t = 0.09 - 0.14$  GeV<sup>2</sup>/c<sup>2</sup> in the figure is

$$\langle A_{pp} \rangle \sim 0.1211 \pm 0.0047. \quad (6.00 \text{ GeV/c})$$

These are dominated by the Rust et al. data (Ref. [7]), with typical statistical uncertainties of  $\pm 0.010$  and a quoted relative systematic uncertainty of  $\pm 7\%$  due to the knowledge of the beam polarization. In fact, they normalized their data to those of Borghini et al. (Ref. [5]).

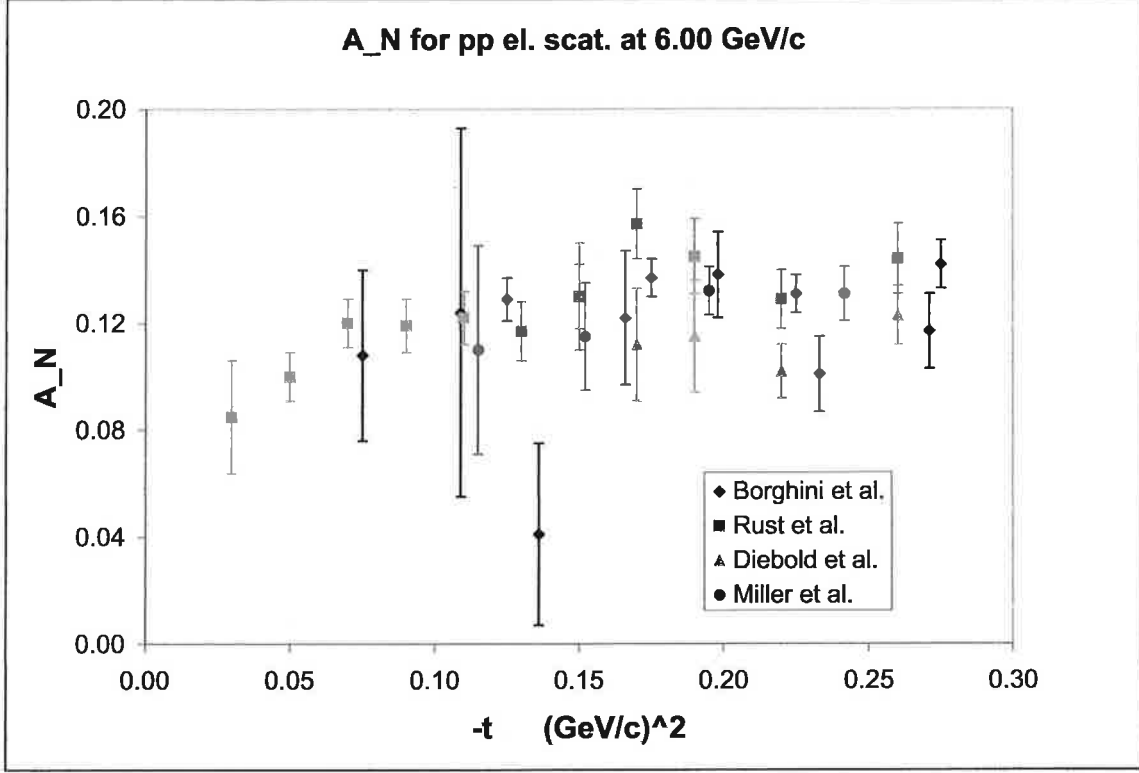


FIG. 3: Measured  $pp$  analyzing power data at a beam momentum of 6.00 GeV/c. The results are from Refs. [5-8].

Thus

$$A_{pp} \simeq 0.1211 \pm 0.010 \pm 0.0085. \quad (6.00 \text{ GeV/c})$$

The typical momentum dependence in this momentum and  $t$  range is  $A_{pp} \sim 1/p_{lab}$ , so

$$A_{pp} \simeq 0.1123 \pm 0.0093 \pm 0.0079. \quad (6.47 \text{ GeV/c}) \quad (6)$$

This result is consistent with those derived earlier from the global fit and thus it will be adopted for the  $pp$  elastic scattering analyzing power for this paper.

With this  $A_{pp}$  and the derived value of  $\epsilon_H$  in Eq. 5, and the assumption that there is no non-elastic background in the forward-backward coincidence counts, then

$$P_B = \epsilon_H/A_{pp} = 0.650 \pm 0.055 \pm 0.046. \quad (7)$$

Combining with the recoil only asymmetries from Tables II and III, using the weighted

average of the two sets of runs,

$$\begin{aligned}
A_{pC} &= 0.0312 \pm 0.0011 \pm 0.0026 \pm 0.0022 \\
&= 0.0312 \pm 0.0036 \\
A_{pF} &= 0.0709 \pm 0.0005 \pm 0.0060 \pm 0.0050 \\
&= 0.0709 \pm 0.0078,
\end{aligned} \tag{8}$$

where the three errors, in order, are due to the statistical uncertainty in the asymmetry measurement, the statistical error in the beam polarization, and the systematic uncertainty in the beam polarization. Only the first error is uncorrelated between the carbon and fishline values.

## V. ACKNOWLEDGEMENTS

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